HEAVY HIGGS PRODUCTIONS AT $\gamma\gamma$ COLLIDERS [a]

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Abstract

Multi-Higgs doublet models include more than one neutral Higgs bosons, some of which have different properties under a CP transformation. We examine their productions at $\gamma\gamma$ colliders. It is found that helicity observations of final top-pairs can be powerful tools to distinguish their CP properties, especially when masses of the Higgs bosons are almost degenerate.

1   Introduction

Searches for Higgs boson(s) and precise measurements of their properties are important to understand the mechanism of the electroweak symmetry breaking. Although the standard model (SM) predicts one neutral CP-even Higgs boson, several extended models of the SM, such as supersymmetric SM (SSM), require more than one Higgs bosons. In such models, neutral CP-odd Higgs boson(s) (A) as well as neutral CP-even Higgs boson(s) (H) appear. Models like the minimal supersymmetric extension of the SM (MSSM) which is one of the two-Higgs doublet models are expected to have almost degenerate masses for H and A if they are heavy in comparison with m_Z. We examine the possibility of observing these Higgs bosons and distinguishing their CP properties at $\gamma\gamma$ colliders in such cases where their mass difference is at most the same order of their total decay widths.

We show that helicity observations of final top-pairs [2] can be powerful tools for our purposes in spite of dull peak distributions of luminosity which are peculiar to $\gamma\gamma$ colliders. This advantage comes from the difference between final $t_L\bar{t}_L$ and $t_R\bar{t}_R$ processes in effects of interference between amplitudes.

In this report, we discuss the detection possibility of heavy neutral Higgs bosons at future $\gamma\gamma$ colliders, especially concentrating on the MSSM case as an example.

2   Helicity dependence of amplitudes

We define spin-zero states decaying into $t_L\bar{t}_L$ and $t_R\bar{t}_R$ systems as $|LL>$ and $|RR>$. These states are interchanged under a CP transformation,

$$\begin{aligned} \mathcal{CP}|LL> &= -|RR> , \\ \mathcal{CP}|RR> &= -|LL> . \end{aligned} \tag{1}$$

Therefore, the CP eigenstates are $45°$ mixtures of $|LL>$ and $|RR>$:

$$\begin{aligned} \mathcal{CP}(|LL>-|RR>) &= +(|LL>-|RR>) , \\ \mathcal{CP}(|LL>+|RR>) &= -(|LL>+|RR>) . \end{aligned} \tag{2}$$

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[a] based on the work in collaboration with J. Kamoshita, A. Sugamoto and I. Watanabe [1].

Table 1: Helicity dependence of the amplitudes for $\gamma\gamma \to t\bar{t}$

	$t_R\bar{t}_R$	$t_L\bar{t}_L$
$\gamma_+\gamma_+$	$\mathcal{M}^{RR}_{cont}$ $\mathcal{M}_{\mathcal{H}}$ $\mathcal{M}_A$	$\mathcal{M}^{LL}_{cont}$ $-\mathcal{M}_{\mathcal{H}}$ $\mathcal{M}_A$
$\gamma_-\gamma_-$	$-\mathcal{M}^{LL}_{cont}$ $\mathcal{M}_{\mathcal{H}}$ $-\mathcal{M}_A$	$-\mathcal{M}^{RR}_{cont}$ $-\mathcal{M}_{\mathcal{H}}$ $-\mathcal{M}_A$

The former CP-even eigenstate corresponds to H and the latter CP-odd eigenstate to A. The CP properties play important roles in the helicity dependence of amplitudes. We here consider the process of $\gamma\gamma \to t\bar{t}$. H and A are produced in s-channel via loops of charged particles. Besides these Higgs production diagrams, tree diagrams also contribute around Higgs mass poles. Thus, amplitudes we have to consider are

$$\mathcal{M}^{\lambda\bar{\lambda}}_{\gamma\gamma\to t\bar{t}} \simeq \mathcal{M}^{\lambda\bar{\lambda}}_H + \mathcal{M}^{\lambda\bar{\lambda}}_A + \mathcal{M}^{\lambda\bar{\lambda}}_{cont} , \qquad (3)$$

denoting the helicities of t and $\bar{t}$ as λ and $\bar{\lambda}$, respectively, and $\mathcal{M}^{\lambda\bar{\lambda}}_H$, $\mathcal{M}^{\lambda\bar{\lambda}}_A$ represent amplitudes of H, A productions, $\mathcal{M}^{\lambda\bar{\lambda}}_{cont}$ of tree diagrams, where the subscript 'cont' means features of the tree diagrams, that is, continuum dependence on center-of-mass energy, $\sqrt{s}_{\gamma\gamma}$.

In Table 1, we show relative signs of helicity amplitudes, where $\mathcal{M}_H$ stands for $\mathcal{M}^{RR}_H$ and $\mathcal{M}_A$ for $\mathcal{M}^{RR}_A$ at $\gamma_+\gamma_+$ collisions. The amplitudes for the tree diagrams are given as follows;

$$\mathcal{M}^{RR}_{cont} = -8\pi\alpha Q_t^2 \frac{m_t(1+\beta_t)}{E_t(1-\beta_t^2\cos^2\theta)} \qquad (4)$$

$$\mathcal{M}^{LL}_{cont} = -8\pi\alpha Q_t^2 \frac{m_t(1-\beta_t)}{E_t(1-\beta_t^2\cos^2\theta)}, \qquad (5)$$

where Q_t, m_t, E_t and β_t are charge, mass, energy and beta factor of top quark in the center-of-mass frame. The absolute value of the amplitude for $t_R\bar{t}_R$ is larger than that for $t_L\bar{t}_L$ due to the difference in factors $(1 \pm \beta_t)$.

First, we consider the case of initial $\gamma_+\gamma_+$. The minus sign of the H amplitude for $\gamma_+\gamma_+ \to t_L\bar{t}_L$ comes from the CP transformation for the final top-pair. As for the A amplitude, the odd contribution is cancelled by another CP-odd factor from the coupling between A and the top-pair. We can see from the analysis that H-A interference is cancelled if the helicities of final top-pairs are not observed.

On the other hand, the CP transformation for initial photons do not induce a minus sign. In the same way as final top-pairs, polarized initial photons lead to non-vanishing H-A interference.

3 Interference between amplitudes

We give numerical estimates of the cross sections for the above processes[3]. To simplify the Higgs sector, we concentrate on MSSM having two Higgs doublets.
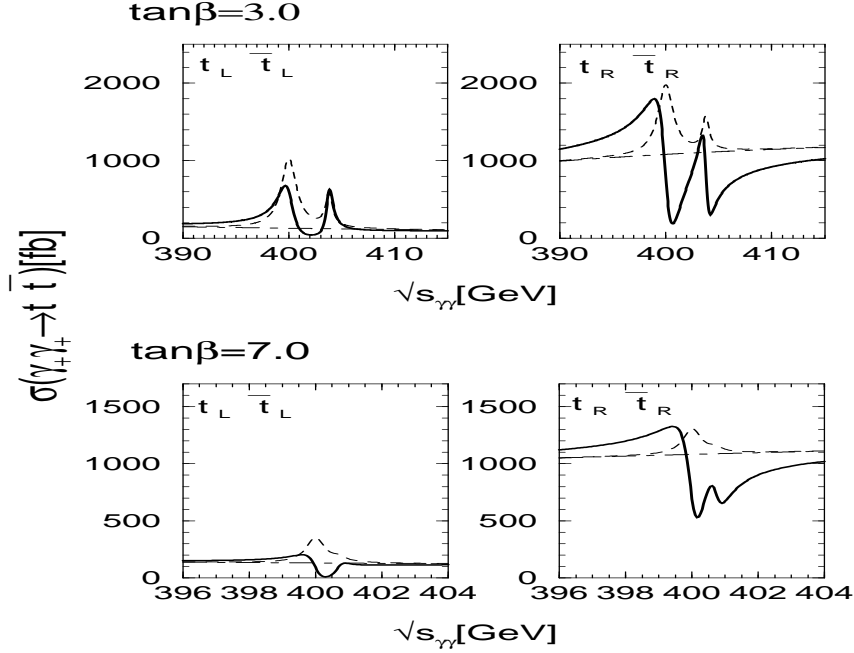
Figure 1: $\sqrt{s}_{\gamma\gamma}$ dependence of bare cross sections for $\gamma_+\gamma_+ \to t\bar{t}$

Then we are able to perform definite numerical estimations by fixing a few MSSM parameters, without losing the essence which are applicable for the more complicated models. We have three states of the neutral Higgs bosons in MSSM, the light Higgs h, the heavy Higgs H and the pseudoscalar Higgs A. The former two are CP-even, and the last CP-odd. In our analyses, we parametrize the Higgs sectors by two parameters, the mass of A, m_A, and the ratio of the vacuum expectation values of two Higgs doublets, $\tan\beta$. In MSSM, the value of the mass of h, m_h, is close to m_A, if A is lighter than Z boson. On the other hand, as m_A becomes heavier, the mass of H, m_H approaches to m_A, and m_h saturates the upper bound of roughly 150 GeV. We now focus on the heavy A case where both H and A can decay into $t\bar{t}$.

Fig.1 shows $\sqrt{s}_{\gamma\gamma}$ dependence of cross sections in the case of $\tan\beta = 3.0$ and 7.0. We took values of MSSM parameters as $M_2 = 500$GeV, $\mu = -500$GeV, $M_{\tilde{f}} = 1000$GeV which give masses to charged SUSY particles in loops and evade large contribution of them owing to their heaviness. We fixed the mass of A to 400GeV, and other parameters, such as the mass of H, total decay widths of H and A, are calculated by HDECAY [4]. The dotted curves represent the cross sections without interference and the dot-dashed ones that without any Higgs production. The effects of interference

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		$\sqrt{s}_{\gamma\gamma} < m_A$	$m_A < \sqrt{s}_{\gamma\gamma} < m_H$	$m_H < \sqrt{s}_{\gamma\gamma}$
$t_R\bar{t}_R$	A–cont	$+$	$-$	$-$
	H–cont	$+$	$+$	$-$
$t_L\bar{t}_L$	A–cont	$+$	$-$	$-$
	H–cont	$-$	$-$	$+$

can be clearly observed by comparing dotted curves with solid ones which are complete cross sections including interference.

Here, we notice on the difference of interference effects between two processes, $\gamma_+\gamma_+ \to t_L\bar{t}_L$ and $\gamma_+\gamma_+ \to t_R\bar{t}_R$. The interference terms are proportional to real parts of the product of two in $\mathcal{M}_{cont}$, $\mathcal{M}_H$ and $\mathcal{M}_A$. Since the absolute values of the continuum amplitudes are larger than that of H, A amplitudes except for near mass poles of two Higgs bosons, the effects from the interference terms between $\mathcal{M}_{cont}$ and $\mathcal{M}_H$, $\mathcal{M}_A$ contribute significantly. Signs of these terms are changed as $\sqrt{s}_{\gamma\gamma}$ goes over the mass poles of H, A. The estimation is shown in Table 2. It can be seen in $t_R\bar{t}_R$ case that constructive effects are expected below m_A, destructive above m_H. In $t_L\bar{t}_L$ case, between the masses of two, the terms contribute destructive. These features can be seen in Fig.1 even in larger $\tan\beta$ where branching ratios of Higgs bosons decaying into top-pairs are smaller due to $\tan\beta$ dependence of their couplings.

4   Convoluted cross sections

Next, we must consider $\sqrt{s}_{\gamma\gamma}$ dependence of luminosity. The convoluted cross sections are obtained as follows;

$$\sigma^*(\sqrt{s}_{ee}) = \int d\sqrt{s}_{\gamma\gamma} \frac{1}{L} \frac{dL(\sqrt{s}_{\gamma\gamma})}{d\sqrt{s}_{\gamma\gamma}} \sigma(\sqrt{s}_{\gamma\gamma}), \tag{6}$$

where $\sqrt{s}_{ee}$ is center-of-mass energy of original electrons and L the $\gamma\gamma$ luminosity. Fig.2 shows the convoluted cross sections for $\tan\beta = 3.0$, 7.0 after considering the cuts for the visible energies in the detector, E_{vis}. Though the remarkable effects of interference for bare cross sections are unfortunately smeared, constructive effects below the H and A masses and destructive effects above the masses remain in $t_R\bar{t}_R$ case. When $\tan\beta$ becomes larger or $t_L\bar{t}_L$ cases are considerd, very high luminosity and careful analyses seem to be required in order to observe the interference effects. However, they certainly have information of the existence of two Higgs bosons which are scalar and pseudoscalar.

5   Summary

We have discussed heavy Higgs productions at $\gamma\gamma$ colliders. It has been found that the helicity observations of final top-pairs can be powerful strategy for
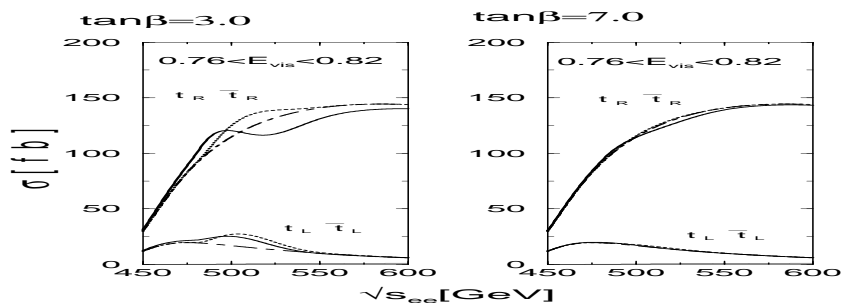
Figure 2: $\sqrt{s}_{ee}$ dependence of convoluted cross sections for $\gamma_+\gamma_+ \to t\bar{t}$

heavy Higgs detections at $\gamma\gamma$ colliders, as long as the Higgs bosons have enough branching ratios of decaying into top-pairs.

A similar method can be performed more clearly for muon colliders via direct $\mu^+\mu^-$ annihilation into H or A, with the muon beam polarization. It will be discussed in a separate paper.

Acknowledgments

References

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